NERVE CONTROL OF THE TEMPO OF MOTION IN MAN AND POSSIBLE METHODS OF REPRESENTING TIME IN THE NERVOUS SYSTEM

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One of the central questions of the problem of perceiving time has long been the question of methods of describing time in the nervous system.

We can select three aspects under which this question is considered. The first is connected with the idea that time perception does not exist in a void, but is connected with measurement of the duration of events, of pauses between individual events, that is, it is connected with the perception of certain signals [3, 5, 11].

The second aspect of consideration deals with representation of subjective time stemming from the characteristics of active processes taking place in the organism. This question has been studied in greatest detail by Bünning [2] insofar as it applies to time intervals which record days, as well as by many researchers insofar as it concerns the interval of 0.6-0.7 sec, which has received the name of "neutral" interval in the literature [3]. In recent years the viewpoint has taken hold that an active part is taken in time measurement in the nervous system not only by vegetative rhythmic processes, but also by an ordered motor system [5, 6]. The third aspect of the question of time representation in the nervous system relates to the search for physiological time counting units. The intense long-standing attention of psychologists to the "neutral" interval is, without doubt, somehow connected with the desire to find a certain subjective time-counting unit in this interval.

But investigations of the "neutral" interval have not lead to distinct and uniform results, the reasons for which have been thoroughly analyzed by Woodrow. To the analysis made by him we might add the absence of clear theoretical ideas on the part of investigators of the "neutral" interval and the absence of attempts to tie in "psychological" time with somatic motor activity.

The first attempt to establish a theory on the representation of time intervals in the nervous system is due to McGill [10], who described a model of an interval generator and considered some applications of this model. The main point of McGill's theory is the idea of the existence of an active nervous mechanism which generates pulses of a rigorously defined frequency and participates in control of the time characteristics of motion.

Although McGill does not examine the neurophysiological foundations for such a mechanism, it should be noted that his theory could be supported by such foundations. Thus, e.g., Eccles, Leinas and Sasaki [9] in 1966 published data on /76
the existence, in the cerebellum, of neurons, whose function is to generate rhythmic discharges of a specific frequency. Similar data have been published by Breitenberg [8].

In our paper [4] we demonstrated that man, in executing a consecutive series of motions with his hands, choosing his tempo independently, works so uniformly that the distribution of intervals during which individual motor cycles are executed agree well with McGill's model.

On the basis of these data we formulated the hypothesis that a uniform work tempo is maintained by virtue of the functioning of a nervous mechanism which generates intervals of fixed frequency, the effector system being turned to this frequency.

Subsequent research convinced us that this hypothesis is in need of being supplemented. Experiments have shown that there exists not a single tempo which can be maintained with high precision. This means that the mechanisms which generate intervals may contain certain sets of intervals which differ from each other. If this is true, then it is possible that there exists a step-type mechanism, as described by Ashby [7], which changes control of the tempo of motion from one value of the generated interval to some other. It is natural to believe that time description in the nervous system may be connected with a set of intervals used to control the tempo of motion.

The problem of our present investigation reduced to a clarification of the problem of the number of different possible speeds of execution by a human being of certain motor activity, of the level of precision with which each of these speeds is maintained, and of the relations between the speed-maintenance function and the function of transition from one speed to another.

We studied the motions of the hand in performing a fixed series of successive key-pressing operations. In the experiments, in which 3 persons participated, we measured the magnitude of the interval during which a motor cycle was completed (t_{mot}) and the length of the total interval (t_o) in which the same fixed sequence of motions was completed.

The problem of the test subject consisted in learning a distinct path of hand motion over the experimental panel while executing 24 button-pressing operations on the panel. After being trained we started the basic series of experiments, during which the test subject repeatedly reproduced the learned sequence, successively changing arbitrarily chosen speeds from the fastest to the slowest.

The structure of the order of the motions made in executing the indicated sequence of actions has the following features.

1. Three consecutive pressing operations in the sequence (1-3, 4-6, . . . , 21-24) are completed moving the hand in the same direction over the panel. /77

2. Each succeeding triad differs from the preceding by a change in direction of hand motion. The different directions are: right, left, clockwise, counterclockwise, diagonally right and diagonally left.

The results of our previous research had shown that the time characteristics in executing such a sequence can be predicted. The time interval during which the triad motor cycle is completed fluctuates but little, and its distribution indicates

specificity [4]. The interval between triads has a more random nature; it is characterized by high dispersion and an asymmetric distribution.

Time of a Motor Cycle While Maintaining and Changing Work Speeds

The instruction prior to beginning the experiment directed the test subject to:

a) choose the fastest speed and repeatedly execute the sequence while adhering to this speed;

b) change the speed by slowing it to the lowest possible value and repeatedly execute the sequence while adhering to this new speed;

c) repeat instruction (b) with regard to the second speed and other speeds. The experiment is terminated after the test subject states that it is difficult or impossible to choose a slower speed.

The results of measuring intervals characterizing the time of completion of a single motor cycle (moving the hand + pressing) are given in Table 1; they show that:

1) each speed chosen by the test subject is related to a stable value of t_{mot}. The dispersion of the values of t_{mot} does not exceed a certain limit;

2) a change in speed is connected with a change in t_{mot} by a value greater than the magnitude of the dispersion.

The results we obtained indicate the presence, in the nervous system, of a set of intervals, and, in conformity with these intervals, the time of completion aspect is the selection of an interval from the set and turning to it. The degree of stability of the speed can be described as a measure of the deviations from the mean value of t_{mot} ($\sigma t_{mot}/t_{mot}$). In analyzing the stability, we found that it was a function of the interval t_{mot} ($\sigma t_{mot}/t_{mot}$ = const). These relations are evident in Table 1.

Similar results were obtained in the work of I. N. Krylov and from the laboratory of M.A. Alekseyev from test subjects tapping a keyboard with his fingers (private communication).

The maintenance of a single tempo and changeover to a different tempo, maintaining the second tempo, and the characteristics of t_{mot} obtained in doing so, agree with Ashby's ideas on two brain control mechanisms [7]. /78

The first mechanism is designed to maintain the control variable within certain given limits. The operation of such a kind of mechanism ensures that the t_{mot} interval is maintained at the level of the given tempo. Then fluctuations of the interval show the limits of the field of the variable and are a real part of the description of the operation of the given mechanism.

The second mechanism illustrated in Ashby's theory, which he called a step function, is designed to transfer the values of the variable from one field to another. The operation of this kind of mechanism can ensure the change in t_{mot} values detected in the experiments. Then the measure of the difference between the values of $t_{mot\,n}$ and $t_{mot\,n-1}$ is essential for a description of the step mechanism. Under conditions of our experiments, when the test subject is instructed to change the tempo to the minimum possible value, a certain threshold value was prescribed for the step function, ΔT. /79

TABLE 1. Length t_{not} and Fluctuations σt_{not} in Executing a Motor Cycle While Maintaining Each of the Chosen Speeds (the Mean Number of Measurements of Each Quantity 70±3)

No. of speed	P-v			G-va			R-va		
	t_{mot}, msec	σt_{mot}, msec	ΔT* msec	t_{mot}, msec	σt_{mot} msec	ΔT* msec	t_{mot}, msec	σt_{mot}, msec	ΔT* msec
1	250	20		325	33		285	33	
2	280	23	30	360	34	35	340	29	55
3	310	21	30	400	30	40	430	30	90
4	340	24	30	475	55	75	520	36	90
5	370	28	30	545	42	70	660	40	140
6	410	24	40	645	46	100	970	44	310
7	450	35	40	740	62	95	1240	61	270
8	500	39	50	835	83	95			
9	570	37	70	1010	68	175			
10	630	55	60	1150	80	140			
11	710	48	80	1335	130	185			
12	770	59	60						
13	850	77	80						
14	1060	85	210						
15	1250	83	190						

* $P(\Delta T > \sigma t_{mot}) = 0.999$.

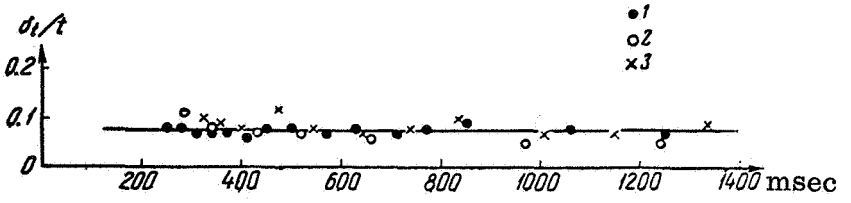

Figure 1. Dependence of $\sigma t_{mot}/t_{mot}$ on the Magnitude of t_{mot} at Various, Arbitrarily Chosen Speeds:
1-2-3, First, Second and Third Test Subjects.

Further analysis of ΔT showed that it depended on the magnitude of t_{mot}, but this relation is of a different nature as compared with the interval-maintenance function. The interval grows on a logarithmic scale, whereas the test subject assumes that it provides a uniform minimum increment to the value of t_{mot}.

The values of t_{mot} with work speeds chosen successively by the test subjects are plotted in a logarithmic scale in Fig. 2. From the figure it is evident that the individual points are arranged fairly well in a straight line, the slope of which describes the step function of the given test subject.

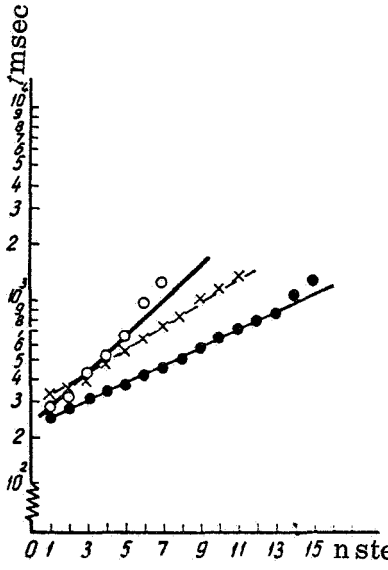

Figure 2. Magnitude of the Intervals of Motor Cycles in the Case of Consecutively Chosen Work Speeds in the Part of the Test Subjects. The Notation is the Same as in Fig. 1.

For the completeness of the characteristics of the two functions it is necessary to say that the number (set) of work speeds for the same test subject fluctuates somewhat in the different experiments, having a tendency to increase with training. Test subject G-va revealed 7 gradations in speed in the first experiment and 11 in the second, R-va revealed 6 gradations in the first experiment and 7 in the second. At the same time it is completely possible that there are a certain number of speeds which describe the individual traits of the test subject. The study of these traits in various people is highly rewarding for purpose of applied psychology. /80

Time of Completion of a Fixed Sequence of Motions While Maintaining and Changing Speeds

The total time of completion of a sequence (t_o) while maintaining and changing work speeds is shown in Table 2. From the table it is evident that while maintaining each speed the interval is very stable, the error in speed precision ($\sigma t_o/t_o$) not exceeding 0.05.

There is also a certain difference between two adjacent intervals ΔT_o, which exceeds the error in precision.

Shown in Fig. 3 are values of t_o for test subject P-va over the entire range of selected work speeds. From the figure we can see both the characteristics of holding t_o precise, expressed as rms deviations, as well as values relating to ΔT_o, representing differences between two adjacent t_o.

TABLE 2. Total Time of Completion t_o in the Case of Arbitrarily Selected Work Speeds

No. of work speed	P–v			G–va			R–va		
	t_o, msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o**, msec	t_o, msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o**, msec	t_o, msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o**, msec
1	6000	0.020		7850	0,029		6840	0.021	
2	6650	0.009	650	8600	0.018	750	8160	0.013	1320
3	7470	0.026	820	9680	0.026	1080	9980	0.017	1820
4	8030	0.018	560 *	11330	0.046	1650	12130	0.018	2150
5	8970	0,014	940	12940	0.007	1610	15450	0.019	3320
6	9920	0.011	950	15490	0.019	2550	22620	0.003	7170
7	10920	0.020	1000	17580	0.031	2090	28850	0.010	6230
8	11960	0.019	1040	19900	0.056	2320 *			
9	13550	0.024	1590	23770	0.012	3870			
10	15010	0.032	1460 *	26980	0.019	3210			
11	16760	0.026	1750 *	31640	0.023	4660			
12	18530	0.015	1770						
13	20030	0.023	1500 *						
14	25240	0.029	5210						
15	30030	0.006	4790						

* $P(\Delta T_o > \sigma_{t_o}) = 0.99$.

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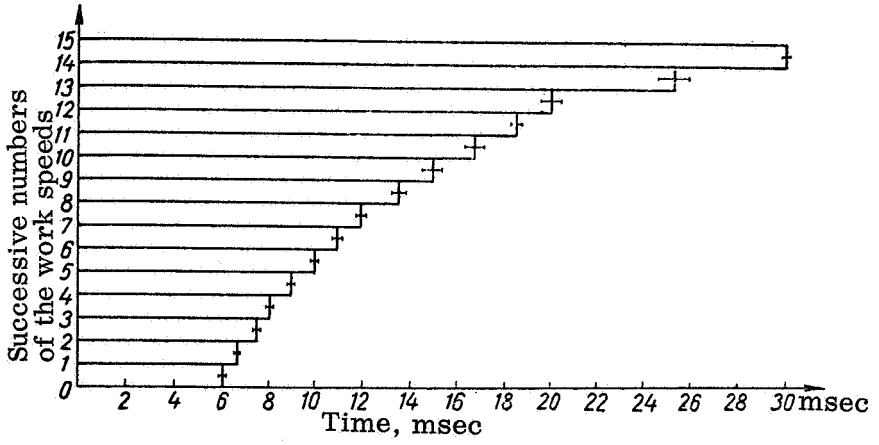

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Figure 3. Total Time of Completion of the Problem (t_o) by Test Subject P-va in the Case of Arbitrarily Chosen Work Speeds. The Errors Indicate σ_t.

Now let us go on the relations between t_o and t_{mot}. Figure 4 presents the interval t_o as a function of t_{mot}, revealing that $t_o = a + kt_{mot}$. Since the interval t_o is a derivative of t_{mot}, it is clear that the characteristics of the functions

representing maintenance of the interval and of the step function are preserved. Here we are faced with the question of the complications in uniform maintenance of the work speed that arise in connection with the conditions of the problem (with the order of the actions in the sequence). Earlier it was demonstrated that sequences consisting of individual organized blocks are described, with respect to time characteristics, by more precise intervals for motions forming a block and by less precise intervals at points separating blocks.

In one of the articles it was shown that the peak is the distribution of these inter-block intervals coincides with the peak of the distribution for intra-block intervals, but the sharp slope of the distribution to the right is responsible for the greater average values of these intervals. In conformity with McGill's model, we consider control of these intervals as control with an error, where there is a probability that jumps or idle cycles of the generator occur. The given sequence contains not less than 3 such separating intervals. At the same time, the interval t_o behaves as if these intervals did not exist. One of the possible explanations of this fact may be that organization of t_o on the level where a decision is made /82 as to the choice of the number of pulses from the rhythm generator is somehow connected with allowance being made for the probability of idle generator cycles.

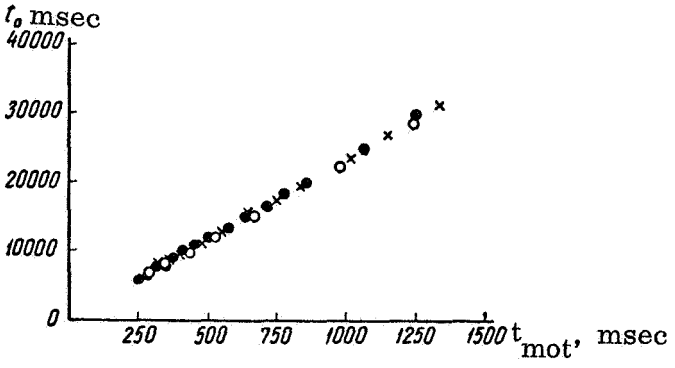

Figure 4. Total Time of Completion of a Problem as a Function of the Length of the Motor Cycle. The Notations 1, 2 and 3 are the same as in Fig. 1.

If it is assumed that this probability does not vary, we can imagine that to execute a sequence a greater number of rhythmic control pulses is needed than there are motions. We suggested that under the given conditions, with a number of motions $n = 23$ (this many motor cycles can be measured for a sequence of 24 motions), the number of control pulses is $n + 1$ with an interval between two pulses of $\tau = t_{mot}$.

Given in Table 3 are the values to which t_o should correspond under this condition, and the values actually found experimentally.

In this case we assumed that agreement between the calculated and experimental t_o can be considered sufficient if the difference between them does not exceed the rms deviation. As evident from the table, where the values representative of the activity of test subject P-va are given, agreement between the theoretical and experimental t_o intervals was observed in 14 out of 15 cases. The same was observed with the other test subjects. Thus, the hypothesis that the total time of completion of a problem is organized by fixing the number of generated intervals with allowance for errors in execution is not without foundation.

However, if control of the interval t_o is so rigorously dependent on the number of rhythmic pulses, the error in execution should obviously lie within the limits of a single pulse. And this means that σt_o should be $\leqslant t_{mot}$. The equivalent data are shown in Table 3, from which it is evident that this relation is valid in all cases. /83

It is very important to emphasize that the described precision of t_o and the simplicity of calculating it are not in direct relationship with the values of the intervals t_{mot}. If we return to a consideration of the rhythmic structure of a sequence, we can see that the average values of t_{mot} for the intervals of motions making up a block are not equal to the intervals which separate consecutive blocks. Hence, all the intervals of motions making up a block are always selected for t_{mot}. As has already been mentioned, the average values of the inter-block intervals are always greater than the corresponding t_{mot}. Thus, the lengths of these two types of intervals can serve as evidence for the rhythmic structure of the sequence (although, as we already wrote, the difference between the average values does not completely reflect the nature of the differences between these intervals).

TABLE 3. Relations Between the Theoretical and Experimental Values of t_o, and Also Between Their Differences, t_{mot} and σt_o, for Test Subject P-va

No. of the work speed	t_{mot}, msec	Computed value of t_o ($t_{mot} \times 24$)	Experimental value of t_o	Δ(t_o theor. to experi.), msec	σ_{t_o}, msec	$\sigma_{t_o} > \Delta$	$t_{mot} > \sigma_{t_o}$
1	250	6000	6000	0	123	+	+
2	280	6720	6650	70	58	−	+
3	310	7440	7470	30	198	+	+
4	340	8160	8030	130	142	+	+
5	370	8880	8970	90	128	+	+
6	410	9840	9920	80	110	+	+
7	450	10800	10920	120	224	+	+
8	500	12000	11960	40	226	+	+
9	570	13680	13550	130	327	+	+
10	630	15120	15010	110	491	+	+
11	710	17040	16760	280	430	+	+
12	770	18480	18530	50	276	+	+
13	850	20400	20030	370	470	+	+
14	1060	25440	25420	20	729	+	+
15	1250	30000	30030	30	177	+	+

Shown in Fig. 5 are data of the experiment with test subject P-v. The hachured columns are the length of the intervals for motions during the transition

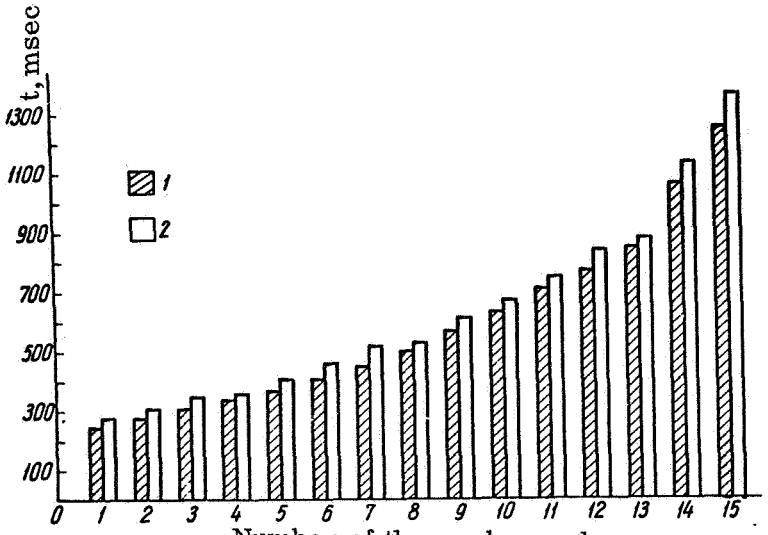

Figure 5. Length of t_{mot} (1) and of the Intervals Separating Organized Blocks (2) at Different Work Speeds for One Test Subject.

from one block to the next for all 15 work speeds. Distinctly evident is the invariant rhythmic structure of the sequence, which we have already described, the control of which is independent of the control of the tempo of work.

CONCLUSION

The experimentally obtained data demonstrate the high precision with which time intervals are repeatedly reproduced in motor activity when the work speed is freely chosen. It turned out that the precision of the intervals for completion of a single motion (t_{mot}) within the limits of 250 to 1250 msec, as described by the relative error in execution, amounts to 0.07 - 0.12 of the length of the interval (7-12%). These figures are found to be in complete agreement with the level of precision of discrimination or reproduction of the corresponding intervals when the intervals are specified by external signals [1, 3].

Thus, it can be assumed that the nervous system (of a mature person) contains a description of a certain set of intervals; the tempo of motion is automatically controlled in conformity with this set and it can be used to measure the length of signal arriving from the outside.

It was further found that the precision with which an organized sequence of actions is performed, a certain interval of the total time of completion (t_o) being reproduced repeatedly, is considerably greater than the precision with which intervals lying within these limits are recognized and reproduced. According to Woodrow, the recognition or reproduction of intervals of 6-30 sec is accompanied by an error of up to 30%; in our experiments, the error is completely an interval of from 6 to 30 sec at various work speeds was 1-5%.

Thus, the execution of an organized sequence of actions sharply defines the reproduction of time intervals. It can be imagined that the measurement of externally prescribed time intervals lying within the limits being considered will be considerably more precise when they are filled with characteristic activity. An examination of the experimental data devoted to this problem will be the subject of discussion in the next publication.

The process of time perception is obviously related to control of the motor activity. This viewpoint is found to be in agreement with the views of Elkin [6] and Smith [5].

We believe that the data presented here contribute to more precise definitions of this viewpoint. These definitions relate to the idea that there exist two functions of control of intervals during which motions are executed, one for maintaining the interval within given limits, the other for changing the interval (Ashby's step function).

The latter, which was up for discussion here, relates to the differences between tempo and rhythm. In accordance with the definition given by Woodrow, we believe that rhythm is a method by which intervals are grouped together.

In preceding investigations [4] we showed that the rhythmic characteristics of executing actions are connected with methods for setting up and storing the order of actions in the memory. The tempo of motions is described either by the number of motions per unit time or by the interval during which an individual motor cycle is completed. In the present article we used the latter description and chose the intervals of motions comprising blocks as such an interval in order not to complicate the description by including the rhythmic characteristics.

Our research has shown that the tempo and rhythm are controlled independently. The rhythm of execution is invariant to a change in tempo, as was demonstrated here.

The temporal organization of a sequence of motions involves separate control of the rhythm and work speed and is related to time description in the nervous system.

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